

Multi-wavelength light curve evolution of Swift J1357.2-0933 during its 2011 outburst

Shan-Shan Weng^{1,2,3*} † Shuang-Nan Zhang^{2,4,5‡}

¹ *Sabanci University, Faculty of Engineering and Natural Sciences, Orhanli–Tuzla, Istanbul 34956, Turkey*

² *Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*

³ *Department of Physics, Xiangtan University, Xiangtan 411105, China*

⁴ *National Astronomical Observatories, Chinese Academy of Sciences, Beijing, 100012, China*

⁵ *Physics Department, University of Alabama in Huntsville, Huntsville, AL 35899, USA*

ABSTRACT

Swift J1357.2-0933 underwent an episodic accretion in 2011 and provided very regular temporal and spectral evolution, making it an ideal source for exploring the nature of very faint X-ray transients (VFXTs). In this work, we present a detailed analysis on both X-ray and near-ultraviolet (NUV) light curves. The fluxes at all wavelengths display a near-exponential decays in the early phase and transits to a faster-decay at late times. The e-folding decay time-scales monotonically decrease with photon energies, and the derived viscous time-scale is $\tau_{\dot{M}} \sim 60$ days. The time-scale in the late faster-decay stage is about a few days. The high ratio of NUV luminosity to X-ray luminosity indicates that the irradiation is unimportant in this outburst, while the near-exponential decay profile and the long decay time-scales conflict with the disc thermal-viscous instability model. We thus suggest that the disc is thermally stable during the observations. Adopting the truncated disc model, we obtain a lower limit of peak accretion rate of $0.03\dot{M}_{\text{Edd}}$ and the X-ray radiative efficiency $\eta < 5 \times 10^{-4}$, which decreases as the luminosity declines. The low X-ray radiative efficiency is caused by the combined action of advection and outflows, and naturally explains that the X-ray reprocessing is overwhelmed by the viscous radiation of the outer standard disc in the NUV regime. We also propose a possibility that the outer standard disc recedes from the central black hole, resulting in the faster-decay at late times.

Key words: accretion, accretion discs — black hole physics — X-rays: binaries — X-rays: stars — X-rays: individual (Swift J1357.2-0933)

1 INTRODUCTION

Low-mass X-ray binaries (LMXBs) are systems in each of them a low-mass companion transfers material via Roche-lobe overflow onto a black hole (BH) or a weakly magnetized neutron star (NS). They spend most time in a dim, quiescent state with a X-ray luminosity of $10^{31-34} \text{ erg s}^{-1}$, but occasionally they undergo bright X-ray and optical outbursts, which are ascribed to a huge increase of accretion rates. Based on their peak X-ray luminosity ($L_{\text{X}}^{\text{peak}}$ in 2–10 keV), LMXBs can be classified into three subclasses: bright ($L_{\text{X}}^{\text{peak}} \sim 10^{37-39} \text{ erg s}^{-1}$), faint ($L_{\text{X}}^{\text{peak}} \sim 10^{36-37} \text{ erg s}^{-1}$), and very faint X-ray transients ($L_{\text{X}}^{\text{peak}} \sim 10^{34-36} \text{ erg s}^{-1}$; Wijnand et al. 2006). At present, it is widely accepted that outbursts of bright X-ray transients arise from the disc thermal-viscous insta-

bility (Chen et al. 1997), which also offers promising explanation for other accretion systems, e.g., dwarf novae and active galactic nuclei. However, the standard disc instability model (DIM) is unable to reproduce the observed long recurrence times nor the typical “fast-rise exponential-decay” light curves; moreover, it produces multiple re-flares which have never been observed (see Lasota 2001 for reviews). There have been several attempts to modify the standard DIM to account for these observed properties, often by invoking irradiation heating (King & Ritter 1998), low α -viscosity (Menou et al. 2000), and truncated disc (Dubus et al. 2001). Taking both the irradiation and truncation effects into account, Dubus et al. (2001) argued that the outburst decay is divided into three stages. First, the X-ray irradiation inhibits the disc from returning to the cool state; the decay is viscous as the thermal equilibrium can be maintained. The light curve shows a near-exponential decay. Second, the accretion rate becomes low enough that the irradiation is not sufficient to ionize the outer edge of the accretion disc; however, the decay rate is still controlled by the irradiation. The light

* E-mail: wengss@ihep.ac.cn

† Current address: Department of Physics and Institute of Theoretical Physics, Nanjing Normal University, Nanjing 210023, China

‡ E-mail: zhangsn@ihep.ac.cn

curves exhibit a linear decay. In the final stage, the irradiation plays no role and light curves quickly decay on a thermal time-scale.

To date, dozens of very faint X-ray transients (VFXTs) have been discovered (Muno et al. 2005). A significant fraction of them have exhibited type I X-ray bursts (Cornelisse et al. 2002; Degenaar & Wijnands 2009), and their companions are fainter than B2 IV stars since no optical and infrared counterpart was detected (Muno et al. 2005). Therefore, it is likely that these sources are LMXBs, and the unusually low outburst luminosity might imply very low time-averaged mass accretion rates in VFXTs. In the DIM framework, if the mean mass transfer rates are much larger than $10^{-14} M_{\odot} \text{ yr}^{-1}$, the duty cycles of transients will be larger than those observed, i.e., frequent outbursts are expected for most sources (Maccarone & Patruno 2013). However, King & Wijnands (2006) pointed out that the mass of a companion can only lose a mass of $< 10^{-3} M_{\odot}$ within a Hubble time if the mean mass transfer rates are less than $10^{-13} M_{\odot} \text{ yr}^{-1}$. That is, the standard LMXBs evolution is too slow for normal stellar-mass companions to reach the very low mass stars ($< 0.1 M_{\odot}$) that probably exist in VFXTs, posing a challenge to the binary evolution theory (King & Wijnands 2006).

The nature of VFXTs is still a puzzle, and our study on VFXTs is hampered by several factors. Due to their relatively faint radiations, the most sensitive X-ray instruments are required to collect good quality spectra and determine their outburst durations. A large number of VFXTs are found close to Sgr A* owing to XMM-Newton/Chandra/Swift monitoring campaigns in the Galactic centre region (e.g., Wijnands et al. 2006; Degenaar & Wijnands 2009). However, near-ultraviolet (NUV)¹ detection is not feasible in the direction of the Galactic centre due to the serious absorption. The outburst durations of VFXTs span from days to months (Degenaar & Wijnands 2009). It is worth noting that we hardly know when outbursts are exactly over due to instrumental limitations, and the values of their outburst durations also depend on the instrument sensitivity. The decay time-scale is a better parameter to describe light curves; however, it is more difficult to estimate because the stochastic variations and irregular profiles usually presented in the light curves of VFXTs. As a result, there is still lack of light curve analysis for VFXTs.

The VFXT, Swift J1357.2-0933, is located at the position of $l = 328.702^{\circ}$ and $b = +50.004^{\circ}$ (Galactic coordinate), and was first detected by *Swift* on 2011 January 28 during its outburst with a low peak luminosity $\sim 10^{35} \text{ erg s}^{-1}$ (Krimm et al. 2011). The short distance ($D \sim 1.5 \text{ kpc}$; Rau et al. 2011) and low extinction in its direction (high Galactic latitude) allow us to obtain a set of NUV data, which had not been available for any VFXT before. Armas Padilla et al. (2013) investigated the correlations between the simultaneous X-ray and NUV luminosities, and argued that its NUV emissions originate from a viscously heated disc instead of the X-ray reprocessing. Analyzing its spectroscopic observations, Corral-Santana et al. (2013) reported that the orbital period of the binary is $2.8 \pm 0.3 \text{ h}$ and the mass of the compact star exceeds $3 M_{\odot}$, making it the first BH VFXT. Its companion is very red, and is estimated to be an unevolved M4 star (Rau et al. 2011). Using the empirical relation between the outburst amplitude and the orbital period of LMXBs, Shahbaz et al. (2013) estimated the V -magnitude of the companion in quiescence to lie in the range $V_{\min} = 22.7$ to

25.6. Assuming that the secondary star is a M4.5 star, they gave a distance $D = 0.5 - 6.3 \text{ kpc}$ based on the distance modulus.

The X-ray and NUV light curves of Swift J1357.2-0933 during its 2011 outburst exhibited relatively simple exponential decay profiles, which are worth a careful study. In this paper, we firstly estimate some basic parameters (e.g., the decay time-scale and the accretion rate), then discuss the origin of its NUV emission, and test the DIM. The *Swift* data reduction is described in the next section. The results and their physical implications are presented in Sections 3 and 4. Conclusion and Discussion follow in Section 5.

2 DATA REDUCTION

Swift is a multi-wavelength observatory with three scientific instruments on board: the Burst Alert Telescope (*BAT*), the X-ray Telescope (*XRT*), and the UV/Optical Telescope (*UVOT*). Swift J1357.2-0933 triggered the *BAT* on 2011 January 28 (Krimm et al. 2011), and then *Swift* executed 43 pointings in the following 7 months. We process both the *XRT* and the *UVOT* data with the packages and tools available in HEASOFT version 6.14.

The *XRT* data were taken in photon-counting (PC) mode before February 1 and after May 13, and the window-timing (WT) mode was used between February 1 and May 13. The initial event cleaning is performed with the task *xrtpipeline* using standard quality cuts. The source light curves are extracted within a circle of radius 25 pixels centred at the source position with *xselect*, while an annulus region with the radius 25 and 50 pixels is adopted for background region. The first observation taken in PC mode is strongly affected by pileup, and thus excluded in this work. The light curves are corrected with the task *xrtlccorr* accounting for telescope vignetting and point spread function corrections due to the geometry of the light curve extraction region. The scaled background rate is then subtracted from the corrected light curves. The net count rates are averaged for each observation, and we also use the spectral fitting results published in Armas Padilla et al. (2013).

The *UVOT* has six filters: *V*, *B*, *U*, *UVW1*, *UVM2* and *UVW2* with a coverage of 1700–6000 Å. The *UVOT* observations were performed in the image mode. When available, the sky image is summed for each observation with *uvotimsum* in order to increase photon statistics. We perform aperture photometry with the summed images by using *uvotsource* with an aperture radius $5''$, and the background flux density is extracted from a neighboring source-free sky region. The NUV flux is calculated by assuming the constant flux density within each filter band, which is read from their response file (version 105). We also correct the integral luminosity in *UVOT* band (2.1–7.8 eV) for the Galactic extinction following the description in Armas Padilla et al. (2013).

3 LIGHT CURVE EVOLUTION

As shown in Figure 1, the fluxes at all wavelengths decrease monotonically and track each other consistently until below the instrument detection limit after ~ 200 days. Figure 1 also shows that the light curves show near-exponential decay in the early phase. We fit the light curves (either count rates or flux) with the exponential function

$$flux = C * \exp(-t/\tau), \quad (1)$$

where C is a constant, t is observational date, and τ is the decay time-scale. The time-scales monotonically decreases with photon

¹ In this paper, we use the term “NUV” to include also the V, B, and U bands.

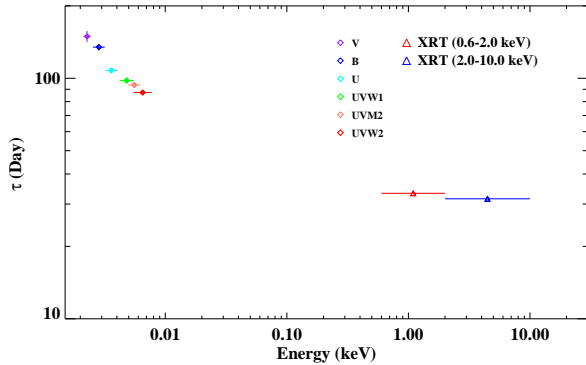


Figure 2. The decay time-scale τ for different energy bands.

energies ranging over four orders of magnitude (Figure 2). The e-folding decay time of X-ray is $\tau_X \sim 30$ days, while the time-scales of longer-wavelength light curves are $\tau_{\text{NUV}} \sim 80 - 150$ days, i.e., $\tau_X/\tau_{\text{NUV}} \sim 0.2 - 0.38$.

Extrapolating the solid line in Figure 1, we expect a X-ray luminosity $L_X \sim 1.8 \times 10^{32} \text{ erg s}^{-1}$ (in 0.5–10.0 keV) on 2011-08-23, corresponding to an absorbed flux of $8.6 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ (in 0.2–10.0 keV), which is above the *XRT* sensitivity². However, *XRT* did not detect the source in the last two observations, indicating that the light curves transit to a faster-decay at late times. The transition should happen between the last observation (2011-07-28) that agrees with the exponential fitting (the solid line in Figure 1) and the first observation (2011-08-23) that deviates from the fitting. The transition luminosity is deduced from the observational time of these two data assuming the exponential decay. We suggest that the transition occurred at the X-ray luminosity of a few times $10^{32} \text{ erg s}^{-1}$ between 2011-07-28 and 2011-08-23 (red boxes region in Figure 1) assuming a distance of 1.5 kpc (Rau et al. 2011).

The *UVOT* data also exist the similar transition. The integral luminosity in *UVOT* band (2.1–7.8 eV) decreases from the peak value of $7.8 \times 10^{33} \text{ erg s}^{-1}$ to $2.9 \times 10^{33} \text{ erg s}^{-1}$ on 2011-05-13, after which time the observations were sparse and only one filter was used for each observation. The *UVM2* observation on 2011-07-28 still follows (at least not significantly deviates from) the exponential decay, indicating that the transition takes place after 2011-07-28. The *UVW1* observations further suggest that the transition happened between 2011-07-28 and 2011-08-18, that is, the light curves of X-ray and NUV might transit almost simultaneously. The NUV light curves present relatively shallower decay, and the NUV luminosity within all six filter bands at the onset of transition is estimated to be $L_{\text{NUV}} \sim (0.9 - 1.1) \times 10^{33} \text{ erg s}^{-1}$ according to the exponential law. Even though entering into a faster-decay phase after 2011-08-18, the source can still be detected by the *U* filter on 2011-08-23, implying that the decay time-scale is of a few days at late times.

Based on the exponential decay scenario, we calculate the NUV luminosity (L_{NUV}) within 2.1–7.8 eV and the ratio of L_{NUV} to L_X (Figure 1). The ratio increases up to 2 to 3 as outburst declines at the onset of light curve deviation from the exponential decay law. When entering into the late faster-decay stage, the fluxes of the last observations with *UVW1* filter (2011-08-11) and *U* filter

(2011-08-23) are lower than those predicted by exponential law by a factor of $\sim 4 - 6$, putting a lower limit of $\frac{L_{\text{NUV}}}{L_X} \geq 0.5$.

4 RADIATIVELY INEFFICIENT ACCRETION FLOWS

The origins of NUV emissions in XRBs are diverse. The strong correlation between the X-ray flux and the NUV flux $L_{\text{NUV}} \propto L_X^\beta$ has been revealed in several sources. Using the *Swift* monitoring data of XTE J1817–330, Rykoff et al. (2007) showed the correlation slope $\beta = 0.47 \pm 0.02$, that is consistent with the value predicted by the X-ray reprocessing model. In contrast, the small values of $\beta \sim 0.2 - 0.38$ observed in the 2011 outburst of Swift J1357.2-0933 implies that the X-ray irradiation contributes little or no NUV emission (Armas Padilla et al. 2013). In this work, we further completely rule out the irradiation hypothesis since the NUV luminosity is close to and even exceeds the X-ray luminosity ($\frac{L_{\text{NUV}}}{L_X} \sim 1$) at late times. On the other hand, the companion is very red and contributes tiny radiations in *UVOT* band with a *V*-magnitude of $V_{\text{vin}} = 22.7 - 25.6$ (Shahbaz et al. 2013). So we confirm that the viscously heated disc is the only option for the NUV emission.

In LMXBs the inner disc is hot, once the accretion rate is below the critical value, the outer disc becomes too cold ($< 10^4 \text{ K}$) and somewhere in between the disc must be unstable. The reason is that in this region the accreted matter is partially ionized, and the hydrogen recombination results in a large change in opacity, affecting the thermal equilibrium. If the instability propagates in the disc, it would trigger re-flares, which are not present in the data of Swift J1357.2-0933. It was widely believed that the irradiation plays a dominant role in LMXB behaviors, e.g., keeping the disc ionized and stabilizing it. Menou et al. (2000) argued that the re-flares can be prevented without the irradiation, if the inner and most unstable part of the accretion disc was replaced by a hot accretion flow and the viscosity parameter was significantly small. However, their model failed to reproduce several important features of light curves (Figure 8 in their paper): 1) The output light curves are markedly different from the exponential shape; 2) The decay time-scales (~ 10 days) are too short; 3) In the final stage, the light curves decay steeply on a thermal time-scale. Lasota (2001) suggested that re-flares were a fundamental property of DIM. The exponential decay profiles without re-flares shown in the outburst of Swift J1357.2-093313 can not be comprehended in the framework of DIM when the irradiation is negligible. In addition, the decay time-scale of a few days in the late faster-decay stage is much longer than the thermal time-scale.

Alternatively, we suggest that the outburst is driven by a stable viscous process, and the whole disc is fully ionized during the *Swift* observations. Assuming that the accretion disc radius R and the kinematic viscosity ν are nearly constant, the surface density is quasi-steady and goes as $\Sigma \simeq -\frac{\dot{M}}{3\pi\nu}$ (King & Ritter 1998; Frank et al. 2002). The mass of the disc can be given by integrating the surface density: $M = 2\pi \int_0^R \Sigma R dR \simeq -\dot{M} \frac{R^2}{3\nu}$, that is, the accretion rate decays as $\dot{M} \propto \exp(-3\nu t/R^2)$. Thus, the light curves would naturally draw out exponential profiles if the luminosity scales as $L \propto \dot{M}^b$.

Investigating the motions of its $\text{H}\alpha$ emission line wings and the double-peak separation, Corral-Santana et al. (2013) suggested that the orbital period of the Swift J1357.2-093313 is 2.8 h, a large inclination $i \sim 70^\circ$, and the mass of the black hole exceeds $3 M_\odot$. The short orbital period points to a small accretion disc, $R_{\text{disc}} \sim$ a few times 10^{10} cm , and the unusually low $L_X^{\text{peak}} \sim 10^{35} \text{ erg s}^{-1}$ corresponds to $\xi \sim 10^{-4}$ Eddington luminosity of a $10 M_\odot$

² http://swift.gsfc.nasa.gov/about_swift/xrt_desc.html

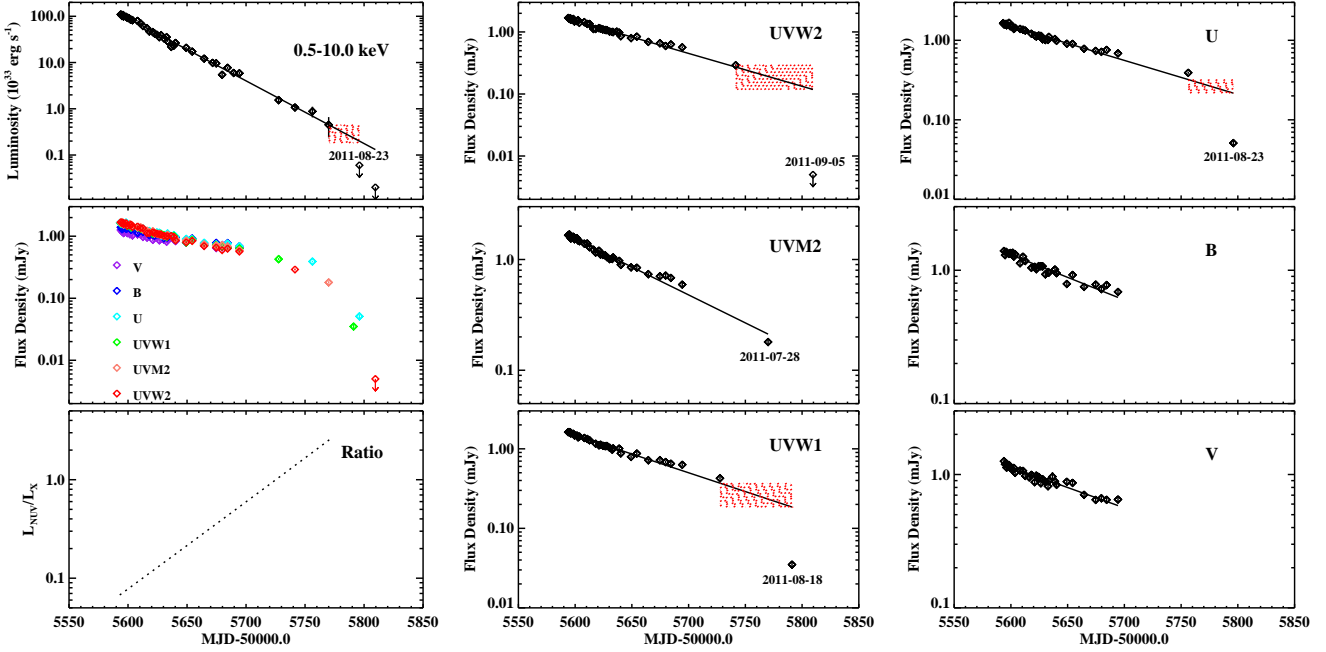


Figure 1. The light curves (diamond points) at different wavelengths are fitted with the exponential function (solid lines). The red boxes mark the time and luminosity intervals of light curve transitions. The ratio of NUV luminosity to X-ray luminosity ($\frac{L_{\text{NUV}}}{L_X}$, dotted line) is calculated with the assumption of exponential decay.

black hole. Both theoretical and observational works suggested that L_X^{peak} increases with orbital periods (e.g., King 2000; Wu et al. 2010). Analyzing a large sample of LMXBs, Kneivt et al. (2014) claimed that the L_X^{peak} of LMXBs with orbital periods of < 4 h would be lowered owing to the transition to the radiatively inefficient accretion flows (RIAFs). Previous X-ray spectral fitting shows an anti-correlation between the photon index (Γ) and the X-ray luminosity (Armas Padilla et al. 2013), which is also found in some other XRBs (Kalemci et al. 2005, 2013; Corbel et al. 2006). Wu & Gu (2008) interpreted this relationship as due to the RIAFs. It means that the outer standard disc is truncated at a transition radius (R_{tr}) by an inner hot accretion flow (see Zhang 2013; Yuan & Narayan 2014 for reviews). Qiao & Liu (2013) employed the truncated disc model to study the relation between Γ and ξ in the sub-Eddington accretion. They argued that at accretion rates (\dot{M}) lower than ~ 0.01 Eddington accretion rate, the inner disc vanishes completely by evaporation, and the accretion is dominated by inner advection-dominated accretion flows (ADAFs, Narayan & Yi 1995), which can produce the anti-correlation between Γ and ξ . Nowadays, it is widely believed that the outer thin disc is restricted beyond a large radius R_{tr} , and the radiation is extremely inefficient at low accretion rates (e.g., Esin et al. 1997; Fender et al. 2004).

For RIAFs, the X-ray luminosity scales as $L_X \propto \dot{M}^{2.0}$ (Russell et al. 2006; Shahbaz et al. 2013) and so $\tau_X \sim 0.5\tau_{\text{M}}$. If the NUV luminosity originates in the viscous thin disc with temperature is $\sim 10^4$ K, the expected correlation in the NUV is $L_{\text{NUV}} \propto \dot{M}^{0.5}$ and so $\tau_{\text{NUV}} \sim 2\tau_{\text{M}}$ (Frank et al. 2002). We therefore have $\tau_X/\tau_{\text{NUV}} \sim 0.25$. On the other hand, in the X-ray reprocessing model, the NUV luminosity is proportional to the X-ray luminosity and scales as $L_{\text{NUV}} \propto L_X^{0.5}$ (van Paradijs & McClintock 1994), i.e., $\tau_X/\tau_{\text{NUV}} \sim 0.5$. The observed low ratio of

$\tau_X/\tau_{\text{NUV}} \sim 0.2 - 0.38$ is consistent with that the NUV emission is dominated by the radiation of the outer non-irradiated viscous disc, and the viscous time-scale is $\tau_{\text{M}} \sim 60$ days.

The emission at the given radius on the outer standard disc is characterized by a (quasi) blackbody of temperature,

$$T(R) = \left\{ \frac{3GM_{\text{BH}}\dot{M}}{8\pi R^3\sigma} \left[1 - \left(\frac{R_*}{R} \right)^{1/2} \right] \right\}^{1/4}, \quad (2)$$

where the black hole mass $M_{\text{BH}} = 10M_{\odot}$ and the innermost stable circular orbit (ISCO) of black hole $R_* = 10^7$ cm are used in our work. For an observer at a distance D , the flux at frequency ν from the outer standard disc is

$$F_{\nu} = \frac{4\pi h \cos i \nu^3}{c^2 D^2} \int_{R_{\text{tr}}}^{R_{\text{disc}}} \frac{R dR}{e^{h\nu/kT(R)} - 1}, \quad (3)$$

where i is the binary inclination (Frank et al. 2002). As discussed above that the whole disc is thermally stable during the transient, we can put a lower limit on the accretion rate by assuming $T(R_{\text{disc}}) = 10^4$ K at the onset of light curve transition. Using equations (2) and (3), we calculate the values of the transition radius R_{tr} and accretion rate \dot{M} for different values of R_{disc} under the condition of $L_{\text{NUV}} = 10^{33}$ erg s $^{-1}$ and $T(R_{\text{disc}}) = 10^4$ K. Figure 3 shows that the outer standard disc is truncated at hundreds to thousands of R_* and $\dot{M} \gg 10^{16}$ g s $^{-1} \sim 10^{-3}\dot{M}_{\text{Edd}}$ ($\dot{M}_{\text{Edd}} = 1.39 \times 10^{18} \times \frac{M}{M_{\odot}}$ g s $^{-1}$) at the onset of light curve transition. Considering the viscous time-scale $\tau_{\text{M}} \sim 60$ days, a lower limit for peak accretion rate $\dot{M}_{\text{peak}} \sim 0.03\dot{M}_{\text{Edd}}$ is deduced from the exponential decay formula.

The observed $L_X^{\text{peak}} \sim 10^{35}$ erg s $^{-1}$ points to a very low X-ray radiative efficiency $\eta = \frac{L_X^{\text{peak}}}{\dot{M}_{\text{peak}} c^2} < 5 \times 10^{-4}$, that is much lower than the value predicted from ADAFs ($\eta > 0.01$ for

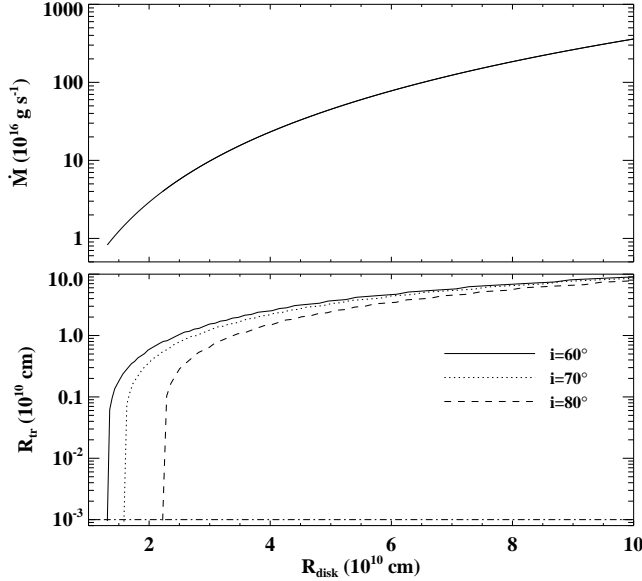


Figure 3. Upper panel: The accretion rate \dot{M} vs. the disc size R_{disc} at the onset of light curves transition. Bottom panel: The transient radii R_{tr} between the standard disc and ADAF for different values of the disc size R_{disc} . The horizontal dot-dashed line represents the ISCO of black hole.

$\dot{M}_{\text{peak}} \sim 0.03\dot{M}_{\text{Edd}}$, Xie & Yuan 2012), indicating that a high proportion of accretion mass is lost in outflows before reaching the central BH. Note that both the radio detection during the outburst analyzed here (Sivakoff et al. 2011) and the quiescent optical/infrared observations of this source (Shahbaz et al. 2013) suggested the existence of a compact jet, supporting significant outflows from this system. Such radiatively inefficient outflows were suggested to exist in other BH LMXBs (e.g., Cyg X-1 and XTE J1118+480). Gallo et al. (2005) found that the large-scale ring-like structure around Cyg X-1 was inflated by the inner jet, and the kinetic energy of dark outflows dominated over radiations. Yuan et al. (2005) fitted the most complete spectral energy distribution (SED; taken in 2000) of XTE J1118+480 with the hot accretion flow model including a jet, and found that the power lost in the outflow exceeded the X-ray and radio emissions by two orders of magnitude. The X-ray re-processing decreases as the X-ray radiative efficiency decreases; on the other hand, the radiative efficiency of the viscous energy release of the outer standard disc is relatively stable depending on R_{tr} only. Eventually, the X-ray reprocessing is overwhelmed by the outer standard disc in the NUV regime.

5 DISCUSSION AND CONCLUSION

In this work, we perform a detailed analysis on both X-ray and NUV light curves of Swift J1357.2-0933 during its 2011 outburst, and obtain the following conclusions.

1. *Decay time-scales.* The light curves at all wavelengths display a near-exponential decay in the early phase and transit to a faster-decay at late times. The e-folding decay time of X-ray is $\tau_X \sim 30$ days, while the time-scales of longer-wavelength light curves are $\tau_{\text{NUV}} \sim 80 - 150$ days, corresponding to a viscous time-scale of $\tau_{\text{M}} \sim 60$ days. This value is similar to that found in bright LMXBs (Chen et al. 1997), implying a similar viscosity pa-

rameter α in bright LMXBs and VFXTs. The time scale in the late faster-decay stage is of a few days.

2. *NUV emission.* We firmly rule out the X-ray re-processing scenario and confirm that the NUV emission is dominated by the viscous energy release of the outer standard disc because of the high ratio of NUV luminosity to X-ray luminosity ($\frac{L_{\text{NUV}}}{L_X} \sim 1$).

3. *Stable RIAFs.* When the irradiation is negligible, the DIM expects the presence of re-flares and a sharp decline (on a thermal time-scale) in the last evolution phase, which conflict with the observations analyzed here. Thus, the outburst duration and recurrence times may not provide valid constraints on the mean mass transfer rates in VFXTs. In contrast, the near-exponential decay profile and the long decay time-scales indicate that the accretion flow is stable during the observations but with very low X-ray radiative efficiency. Adopting the truncated disc model, we obtain a lower limit of peak accretion rate $\sim 0.03\dot{M}_{\text{Edd}}$ and the X-ray radiative efficiency $\eta < 5 \times 10^{-4}$, which decreases as the luminosity declines. We stress that the low efficiency is not just because of advection but also outflows, and our model may also work for VFXTs which contain NSs.

As pointed out by Shahbaz et al. (2013), the distance of Swift J1357.2-0933 is very uncertain, ranging between 0.5 and 6.3 kpc; therefore, its distance might be significantly different from 1.5 kpc used above. We recalculate R_{tr} and \dot{M} for different values of distance under the condition of $L_{\text{NUV}} = 1.0 \times 10^{33} \times (\frac{D}{1.5\text{kpc}})^2 \text{ erg s}^{-1}$ and $T(R_{\text{disc}}) = 10^4 \text{ K}$. In our model, the obtained \dot{M} is not sensitive to the distance; however, the X-ray luminosity increases with D . Therefore, the inferred X-ray radiative efficiency increases with L_X and also D . Note that the classification of bright, faint, and very faint X-ray transients based on L_X^{peak} is somewhat arbitrary. As a matter of fact, the BH LMXB XTE J1118+480 has a brighter X-ray luminosity ($L_X \sim 2 \times 10^{36} \text{ erg s}^{-1}$) but shares a lot of observational properties with Swift J1357.2-0933, e.g., located at high latitude, short orbital period, spectral type (Gelino et al. 2006; Shahbaz et al. 2013). If Swift J1357.2-0933 is at 5 kpc, the inferred X-ray luminosity $L_X \sim 10^{36} \text{ erg s}^{-1}$, the accretion rate $\geq 0.03\dot{M}_{\text{Edd}}$, and the X-ray radiative efficiency $\eta < 5 \times 10^{-3}$ at the peak of outburst (Figure 4) are close to the SED fitting results of XTE J1118+480 (Yuan et al. 2005). Swift J1357.2-0933 can be treated as a cousin of XTE J1118+480.

At present, it is still unclear how the companion supplies such high accretion rate. It was considered that the companion star can be heated by the accretion disc, and the mass-transfer rate would be significantly enhanced when the irradiation dominates the emission of the companion star, (e.g. Lasota 2001; Viallet & Hameury 2007). It is worth noting that the intrinsic emission of the secondary is extremely faint. Thus, if the accretion disc emitted a moderate X-ray luminosity before the outburst, its heating might be much greater than the intrinsic emission of the companion star and trigger the outburst. However, there is lack of observations before the outburst and a plausible mechanism for the mass-transfer instability, and the origin of the high accretion rate is still an open question.

4. *Faster-decay stage.* The long decay time-scale in the late faster-decay stage can not be explained by the irradiation effect nor the thermal instability. We propose a possibility that the faster decay behavior can be interpreted as due to the outer standard disc receding from the central BH. Since the radial velocity in ADAFs is large, its accretion time-scale is negligible. Therefore, the viscous time-scale is determined by the size of outer standard disc $\tau_{\text{M}} \sim \frac{R_{\text{disc}} - R_{\text{tr}}}{\bar{v}_r}$, where \bar{v}_r is the mean radial velocity in the outer standard disc. If the transition radius R_{tr} expands outward

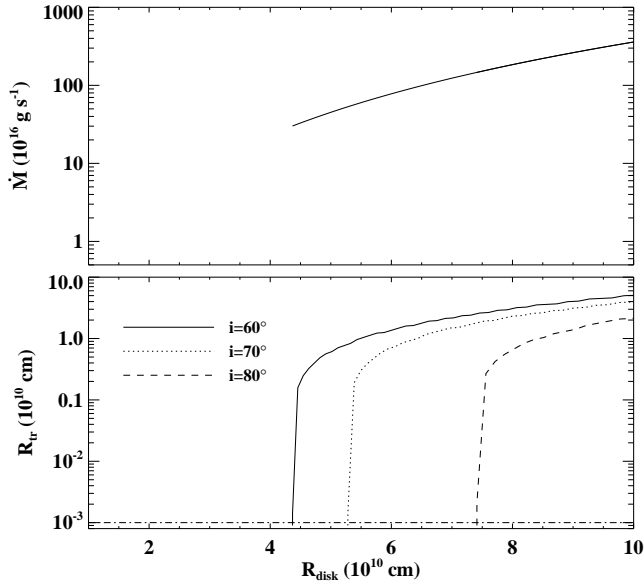


Figure 4. The same as Figure 3 but with $d = 5 \text{ kpc}$ under the conditions of $L_{\text{NUV}} = 1.1 \times 10^{34} \text{ erg s}^{-1}$ and $T(R_{\text{disc}}) = 10^4 \text{ K}$.

at the velocity of \bar{v}_r , the viscous time-scale becomes shorter, leading to a quicker depletion of accretion disc mass and a faster-decay of X-ray luminosity. In the meantime, less NUV emission is produced from the smaller area (due to the increase of R_{tr}) of the outer standard disc. If R_{tr} increases by $\sim (0.1 - 0.2) R_{\text{disc}}$ within ~ 10 days, the NUV emission decreases by a factor of a few. This model predicts that the light curves of X-ray and NUV (quasi)-simultaneously transit from an exponential decay to faster-decay, which can be checked by denser multi-wavelength observations in the future.

ACKNOWLEDGEMENTS

We would like to thank the referee for helpful suggestions and comments that improved the clarity of the paper. S.S.W. thanks Weimin Gu for many valuable suggestions. This work is partially supported with funding by 973 Program of China under grant 2014CB845802, the National Natural Science Foundation of China under grants 11133002, 11373036, and 11303022, the Qianren start-up grant 292012312D1117210, and by the Strategic Priority Research Program “The Emergence of Cosmological Structures” of the Chinese Academy of Sciences, Grant No. XDB09000000. S.S.W. is funded by the Co-Circulation Scheme, supported by the EC-FP7 Marie Curie Actions-People-COFUND and TÜBİTAK.

REFERENCES

Armas Padilla, M., Degenaar, N., Russell, D. M., Wijnands, R. 2013, MNRAS, 428, 3083
 Chen, W., Shrader, C. R., Livio, M. 1997, ApJ, 491, 312
 Corbel, S., Tomsick, J. A., Kaaret, P. 2006, ApJ, 636, 971
 Cornelisse, R., Verbunt, F., in’t Zand, J. J. M., et al. 2002, A&A, 392, 885
 Corral-Santana, J. M., Casares, J., Muñoz-Darias, T., et al. 2013, Sci, 339, 1048
 Degenaar, N., Wijnands, R. 2009, A&A, 495, 547
 Dubus G., Hameury J. M., Lasota J. P., 2001, A&A, 373, 251

Esin, A. A., McClintock, J. E., & Narayan, R. 1997, ApJ, 489, 865
 Fender, R. P., Belloni, T. M., & Gallo, E. 2004, MNRAS, 355, 1105
 Frank J., King A., Raine D. J., 2002, Accretion Power in Astrophysics: Third Edition
 Gelino, D. M., Balman, S. & Kiziloglu, U. et al., ApJ, 642, 438, 2006
 Kalemci, E., Dinçer, T., Tomsick, J. A., et al. 2013, ApJ, 779, 95
 Kalemci, E., Tomsick, J. A., Buxton, M. M., et al. 2005, ApJ, 622, 508
 King A. R., 2000, MNRAS, 315, L33
 King A. R., Ritter H., 1998, MNRAS, 193, L42
 King, A. R., Wijnands, R. 2006, MNRAS, 366, L31
 Kneivitt, G., Wynn, G. A., Vaughan, S., Watson, M. G. 2014, MNRAS, 437, 3087
 Krimm, H. A., Barthelmy, S. D., Baumgartner, W., et al. 2011, The Astronomer’s Telegram, 3138, 1
 Lasota, J. P. 2001, New Astron. Rev., 45, 449
 Maccarone, T. J., Patruno, A. 2013, MNRAS, 428, 1335
 Menou, K., Hameury, J. M., Lasota, J. P., & Narayan, R. 2000, MNRAS, 314, 498
 Muno, M. P., Pfahl, E., Baganoff, F. K., et al. 2005, ApJ, 622, L113
 Narayan, R., Yi, I. 1995, ApJ, 444, 231
 Qiao, E. L., Liu, B. F. 2013, ApJ, 764, 2
 Rau, A., Greiner, J., Filgas, R., 2011, The Astronomer’s Telegram, 3140, 1
 Rykoff, E. S., Miller, J. M., Steeghs, D., & Torres, M. A. P., 2007, ApJ, 666, 1129
 Russell, D. M., Fender, R. P., Hynes, R. I., et al. 2006, MNRAS, 371, 1334
 Shahbaz, T., Russell, D. M., Zurita, C., et al. 2013, MNRAS, 434, 2696
 Sivakoff, G. R., Miller-Jones, J. C. A., Krimm, H. A., 2011, The Astronomer’s Telegram 3147, 1
 van Paradijs, J., McClintock, J. E., 1994, A&A, 290, 133
 Viallet, M., & Hameury, J. M. 2007, A&A, 475, 597
 Wijnands, R., in’t Zand, J. J. M., Rupen, M., et al. 2006, A&A, 449, 1117
 Wu, Q. F., Gu, M. F. 2008, ApJ, 682, 212
 Wu, Y. X., Yu, W., Li, T. P., Maccarone, T. J., & Li, X. D. 2010, ApJ, 718, 620
 Xie, F. G., Yuan, F. 2012, MNRAS, 427, 1580
 Yuan, F., Cui, W., & Narayan, R. 2005, ApJ, 620, 905
 Yuan, F., Narayan, R. 2014, ARA&A, 52, 529
 Zhang 2013, FrPhy, 8, 630